The Technology Whitespace for Deep Decarbonization of Steel Production

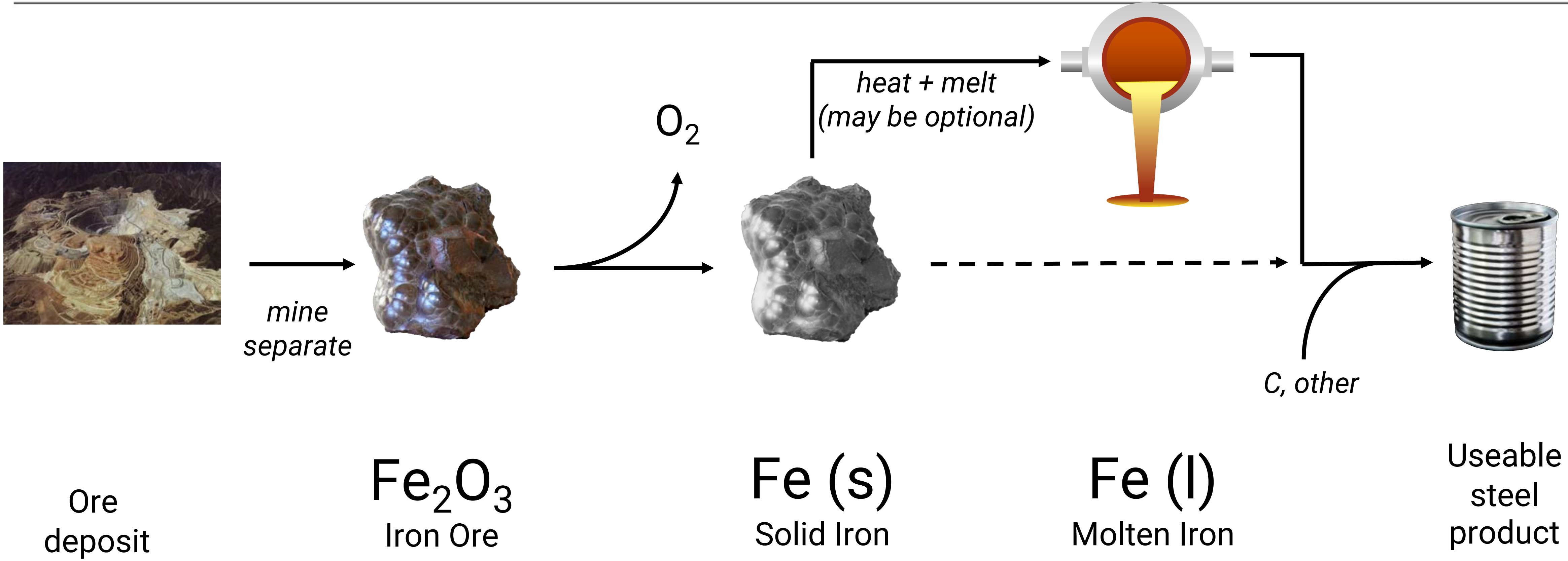
Christina M. Chang, Ph.D.
ARPA-E Fellow

Tuesday, August 31, 2021
Zero-Emissions Iron- and Steelmaking Workshop

christina.chang@hq.doe.gov

These slides will be made available on the ARPA-E website after the Workshop.

Fundamental steelmaking steps

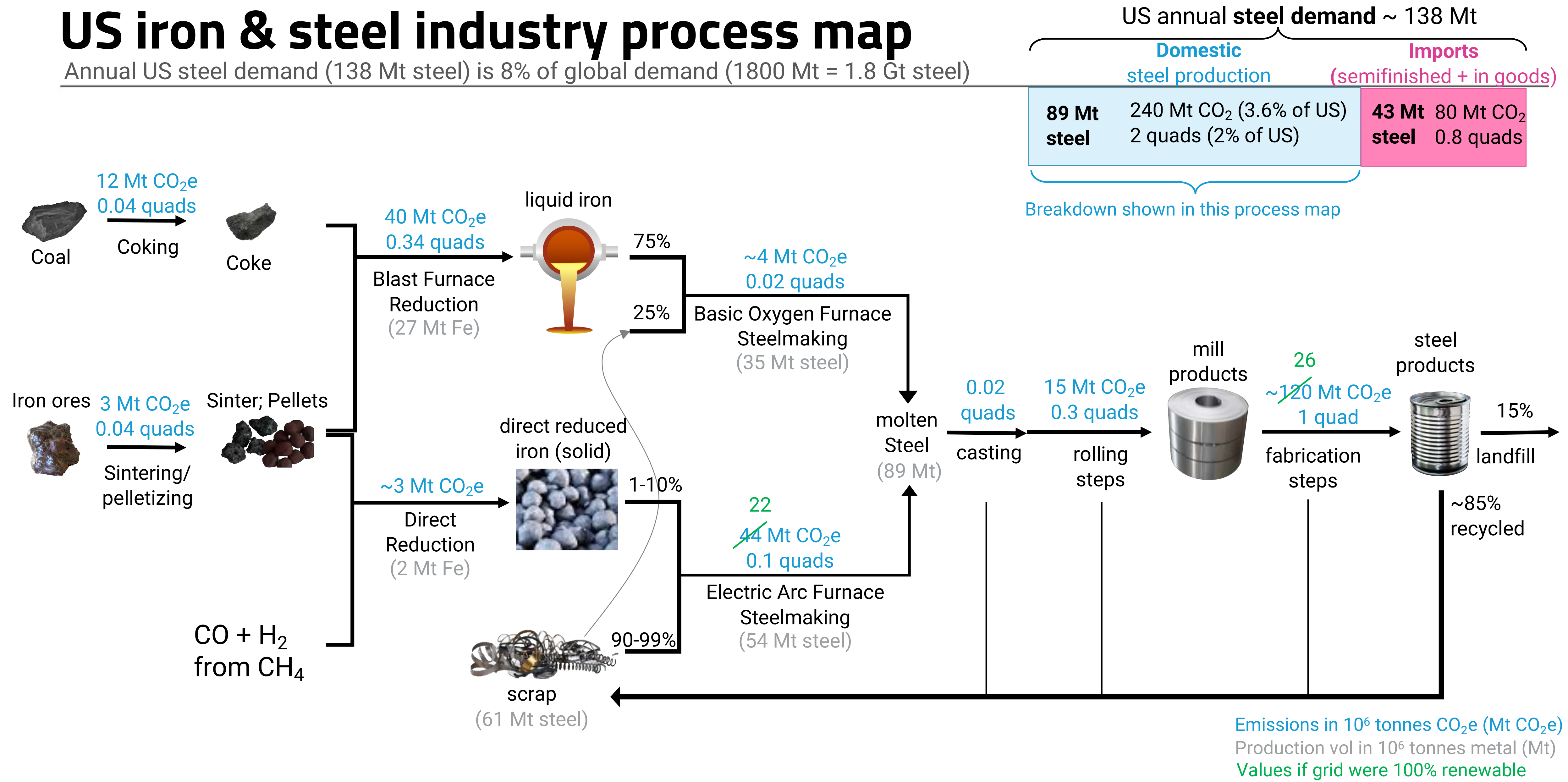


New Constraints:

- Process emissions: 0
- Full lifecycle emissions: as low as possible

US iron & steel industry process map

Annual US steel demand (138 Mt steel) is 8% of global demand (1800 Mt = 1.8 Gt steel)



Reimagined steel industry process map

US annual **steel demand** ~ 138 Mt

Domestic
steel production

138 Mt steel | **0 process CO_2e**
< 3 quads (< 3% of US)

clean electricity

Reduce Ore with Carbon
CCUS, carbon looping, biomass, plastics, and beyond

Reduce Ore Electrochemically
Ore electrolysis (disproportionation)

Reduce Ore with Hydrogen & Hydrogen Plasma
Non-C renewable reductants, e.g. H_2 and H_2 Plasma

BOF or EAF → molten steel

integrated steelmaking

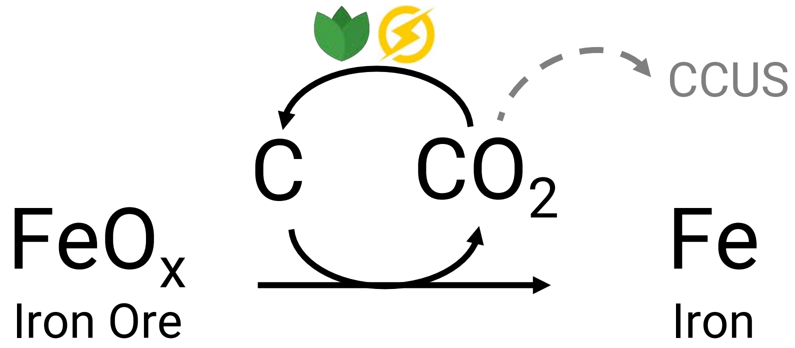
casting, rolling, etc. → mill products

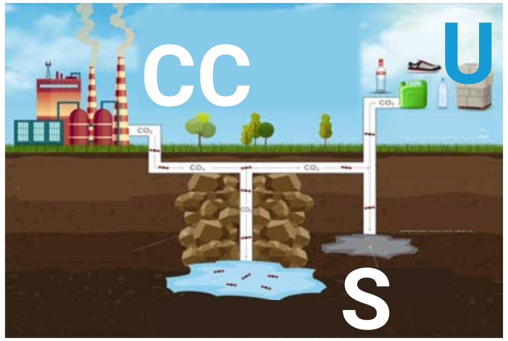
fabrication → steel products

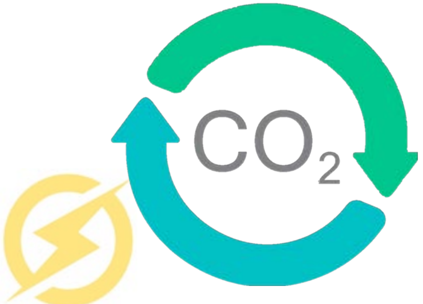
arpa·e
CHANGING WHAT'S POSSIBLE

Reducing ore with carbon

Tuesday Breakout Session







Carbon Capture, Utilization & Storage (CCUS) Retrofit

- How prevalent will CCUS retrofit become in the U.S. by 2050?
- As industry and FECM take the lead, is there a role for ARPA-E?

Biomass

- Land use & land use change?
- Food & land competition?
- Zero-emissions processing to convert biomass into bioreductant form (dehydration)?

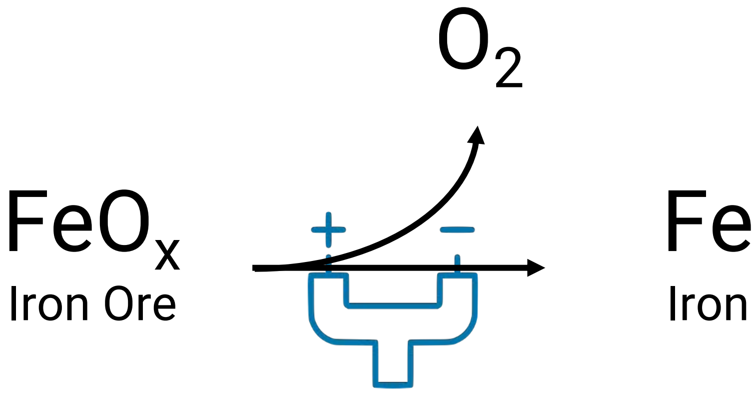
Synthetic renewable C reductants

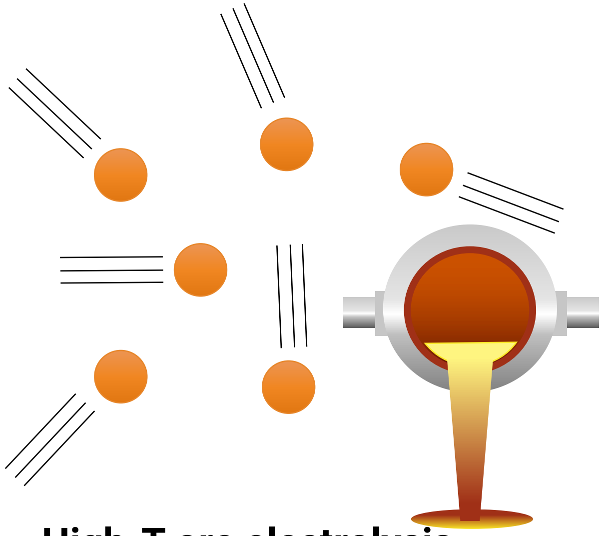
- E.g., CO from direct air capture or flue stream; carbon looping
- What new reactors will be required for carbon molecules of the future renewable carbon economy?

CHANGING WHAT'S POSSIBLE

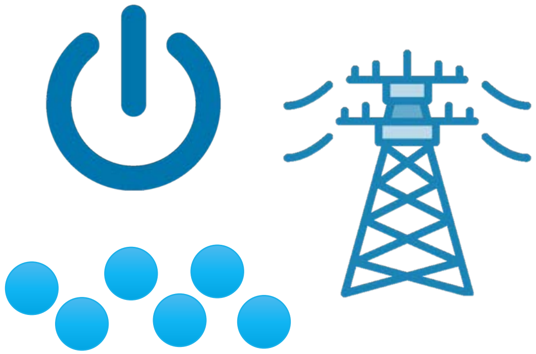
Reducing ore electrochemically

Tuesday Breakout Session

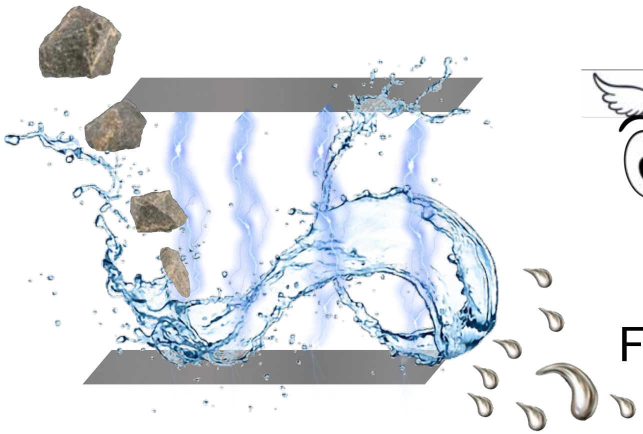




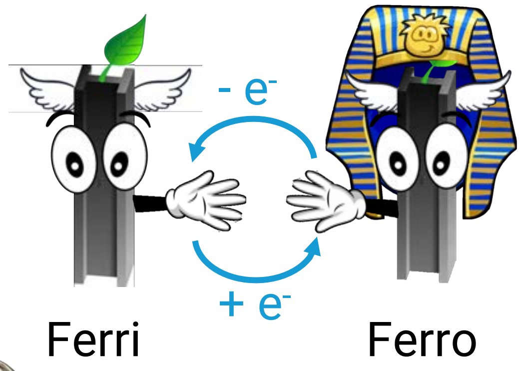
High-T ore electrolysis
- fast reactions and diffusion
- molten Fe product



Low-T ore electrolysis
- on-off flexibility to run only while electricity is ultra cheap
- potentially low capital cost
- solid Fe product



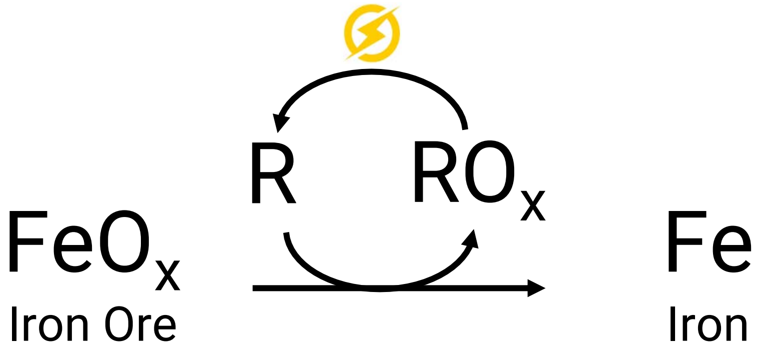
Faster charge transfer with novel electrode designs:
- 3D electrodes?
- continuous flow reactors?



Avoid redox shuttling which wastes energy

Reducing ore thermochemically without carbon

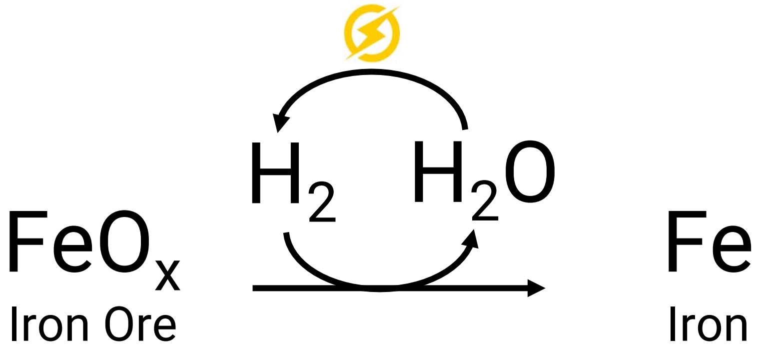
Tuesday Breakout Session

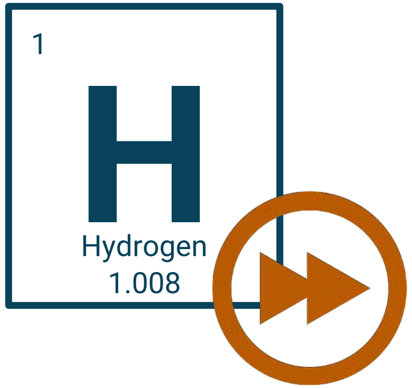


What options exist?

Reducing ore with hydrogen and hydrogen plasma

Tuesday Breakout Session





H_2 Gas-Based Ironmaking

- What innovations / avenues could reduce H_2 ironmaking cost very quickly, to dramatically accelerate deployment timeline?

H_2 Plasma-Based Ironmaking

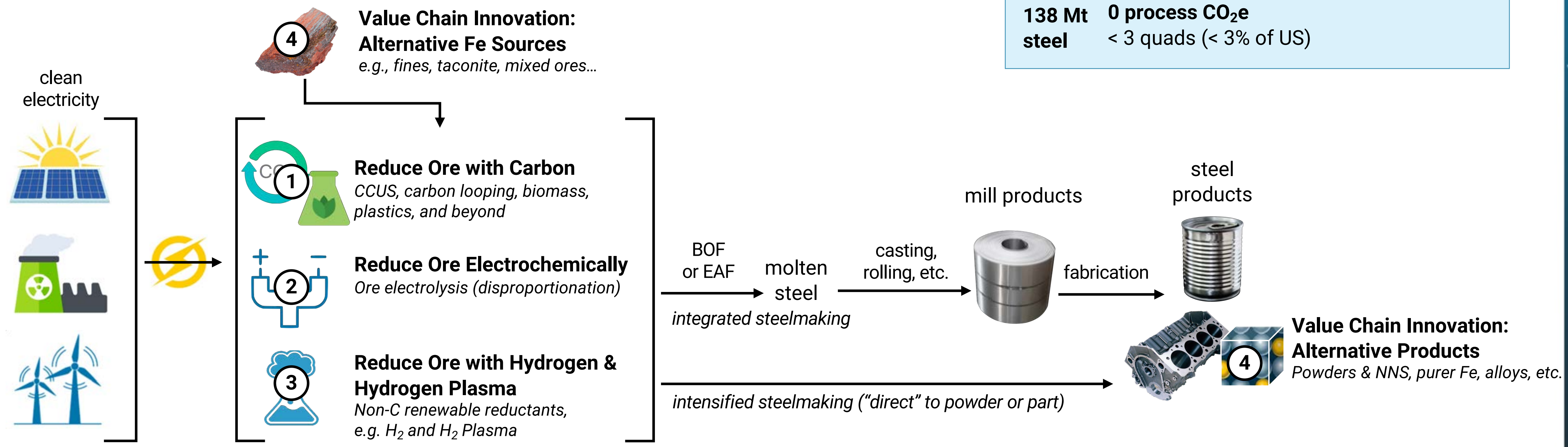
- What R&D could put us on a path to have this tech ready and by the time H_2 price has declined?

Reimagined steel industry process map

US annual **steel demand** ~ 138 Mt

Domestic
steel production

138 Mt steel	**0 process CO_2e** < 3 quads (< 3% of US)



Value Chain Innovation: Alternative Fe sources

Tuesday Breakout Session

Steel Industry "Wastes"

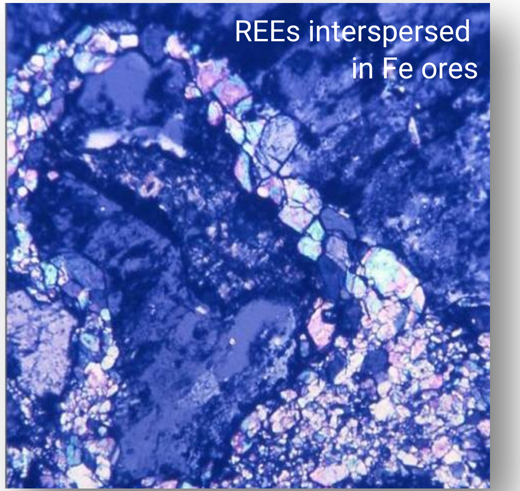
- Tailings, BF dust, etc.
- What annual tonnage of Fe could be produced? How does that value compare with our potential scalability metric?
- What R&D is truly disruptive?

Low-grade Ores

- Taconite, chert-magnetite, etc.
- Can solvent extraction or leaching isolate Fe from SiO_2 or other byproducts?

Iron Ore Fines

- What new, green ironmaking processes can be designed to utilize fines?
- Can fines give rise to new products, like Fe powders?



Mixed-metal ores

- What separations technologies will unlock these ores cost-effectively?
- Can the co-sale of other metals create viable value propositions?

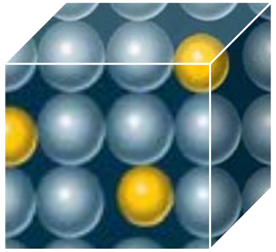
Value Chain Innovation: Alternative Products

Tuesday Breakout Session

Powders from fines?

Near net shape

New alloys



Pure Fe intermediate

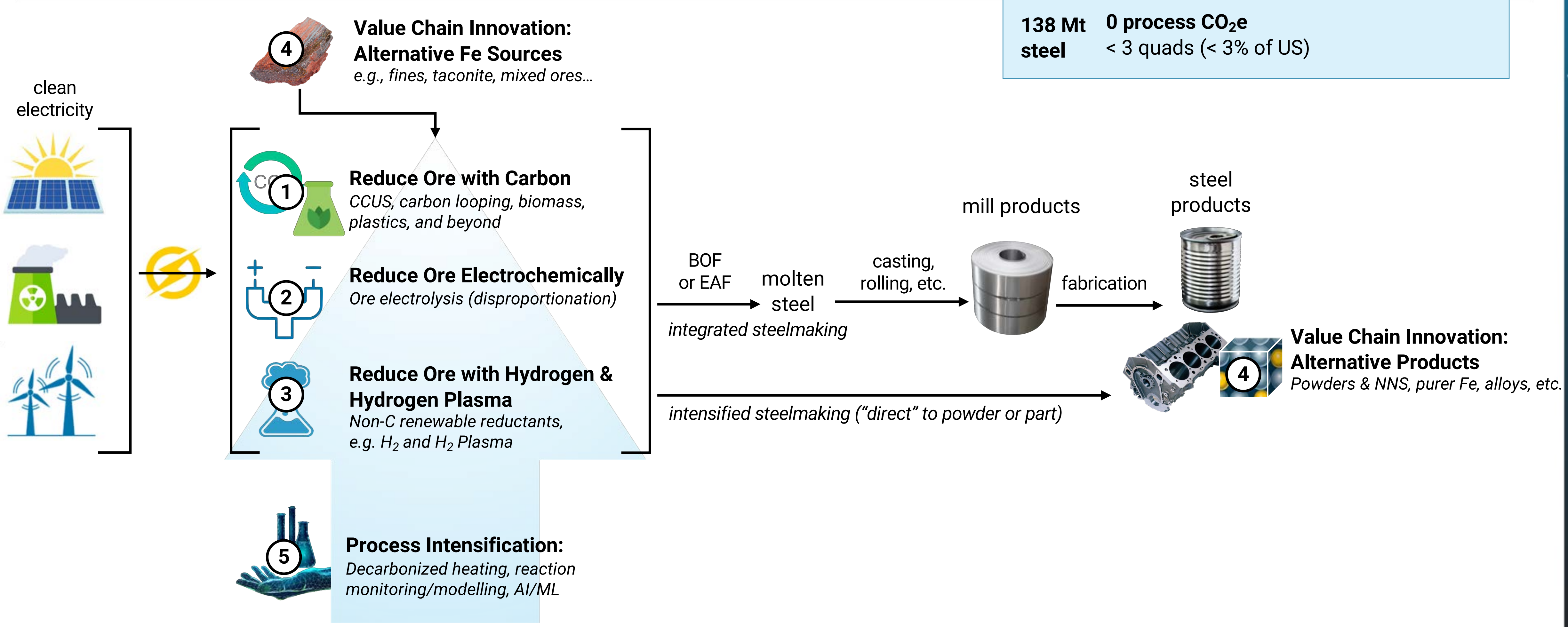
Electrical steel and other ultralow-C steels

- How will the breakdown of steel product demand change over time?
- Can cleanly-powered technologies make steel products that will be in increasing demand?
- Flexibility for new green ironmaking processes process to not only make specialty products, but also translate to wider commodity steel compositions is desirable, to mitigate the CO_2e from commodity steels as well.

Reimagined steel industry process map

US annual **steel demand** ~ 138 Mt

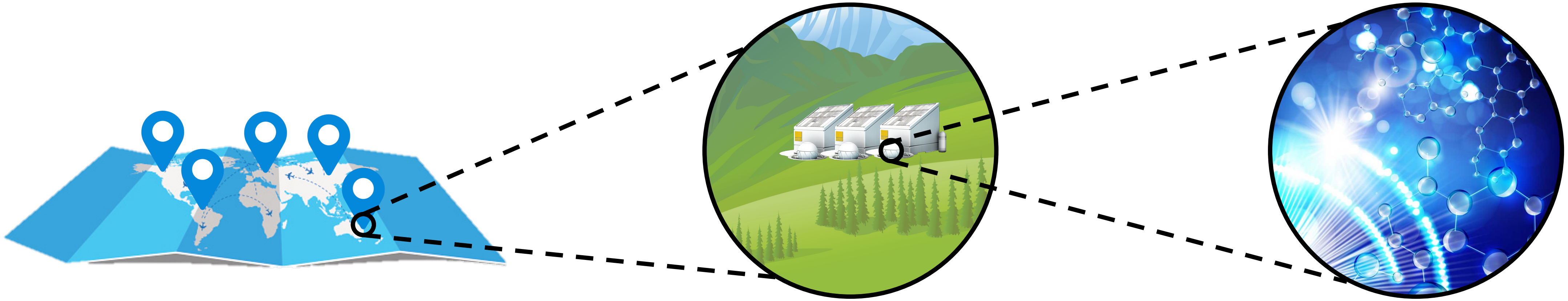
Domestic
steel production



Process Intensification

Wednesday Breakout Session

Cross-cutting principles and tools for developing the next generation of ironmaking technologies



1. System level
How will regional and (inter)national factors[a] shape the future distribution of ironmaking tech?

2. Facility level
Are modular design & deployment and flexible operation a good strategy for (some) future ironmaking technologies?

3. Microscopic level
What process-intensifying techniques[b] will enable in green iron- and steelmaking?

Digital Tools

- Modelling, monitoring, visualization, digital twins, gamification, AI/ML

Decarbonized Heating

- Electrotechnologies: microwave, EAF, plasma heating, induction, resistive, etc.
- Renewable Fuels: biomass, synthetic electrofuels (hydrogen, ammonia, methanol)

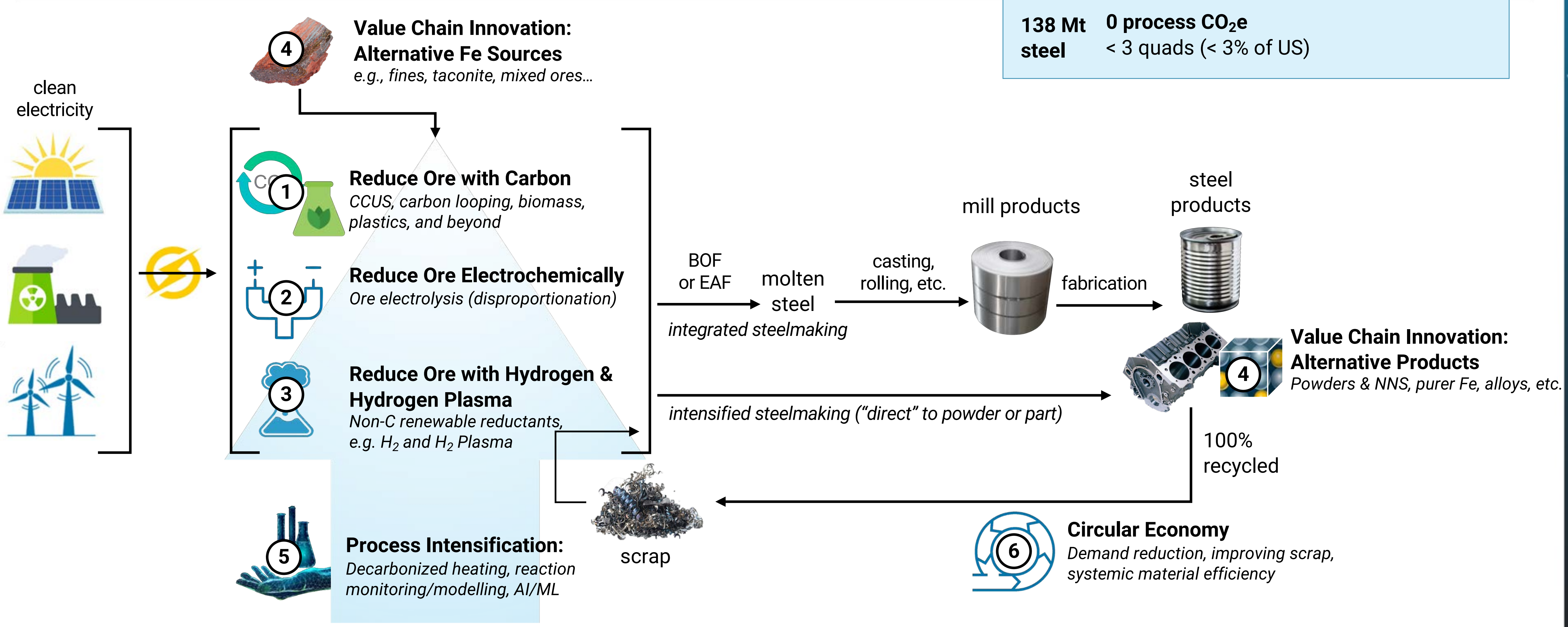
arpa·e CHANGING WHAT'S POSSIBLE

a) transportation costs, policy, availability of resources (land, renewable electricity, scrap, human capital), etc.

b) hybrid separations, integrating reaction with separation, with heat exchange, or with phase transition, techniques using light, ultrasound, or intensive mixing, new process-control methods, etc.

Reimagined steel industry process map

US annual **steel demand** ~ 138 Mt
Domestic
steel production

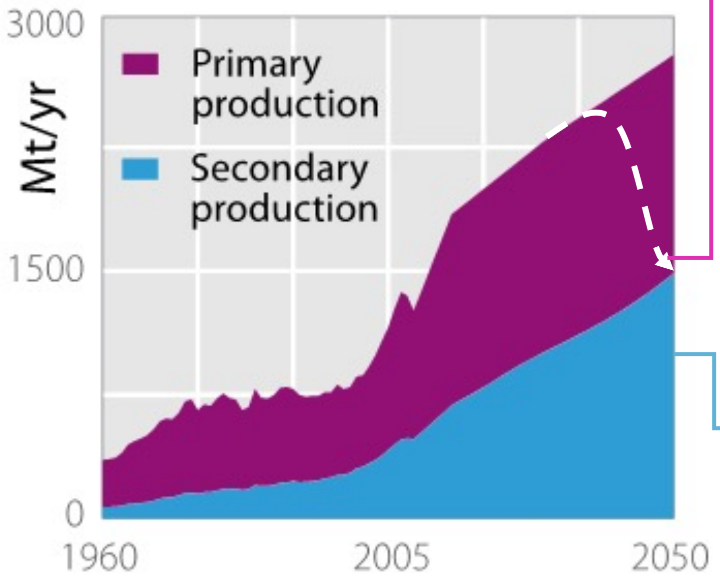


arpa·e
CHANGING WHAT'S POSSIBLE

Circular Economy

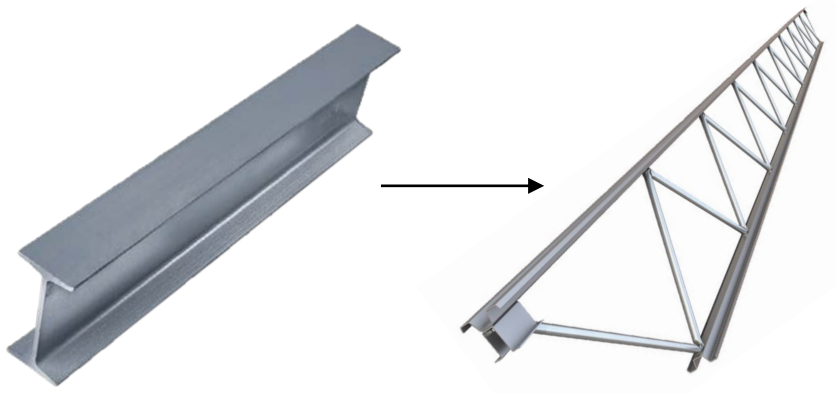
Wednesday Breakout Session

Technologies to Improve Scrap, Material Recycling, and Systemic Sustainability



Systemic Sustainability

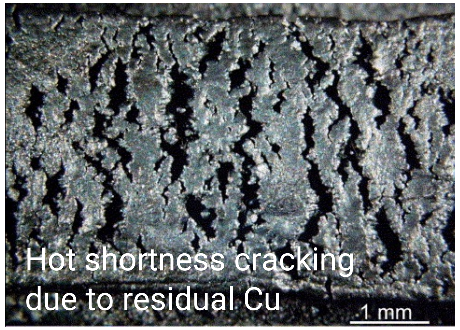
- Could the energy and CO_2e savings of technology to reduce primary demand reduction surpass those of new green steelmaking technologies?



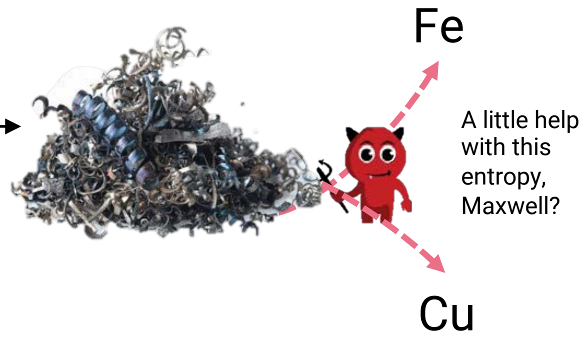
- Use less metal by design, e.g. lightweighting
- Re-use metal components
- Longer lifetime and more intense use
- Societal demand reduction (e.g., ride-sharing)

Technologies to Improve Scrap Recycling

- How could we recover prime scrap (high purity Fe) cheaper than virgin ironmaking?



~50 lbs of Cu in a car



The future of steel: time to wake up (2016), Allwood.

Garza and Van Tyne, Journal of Materials Processing Technology, 159, 2, 2005 pp. 169-180. doi: 10.1016/j.jmatprotec.2004.05.004

The Workshop's 8 Breakout Sessions

US annual **steel demand** ~ 138 Mt

Domestic
steel production

138 Mt steel | **0 process CO_2e**
< 3 quads (< 3% of US)

Legend:
- Tuesday Breakouts
- Wednesday Breakouts
- ARPA-E Breakout Facilitators
- External speakers

Dr. Doug Wicks, Prof. Brajendra Mishra

4 Value Chain Innovation: Alternative Fe Sources
e.g., fines, taconite, mixed ores…

Dr. Jack Lewnard, Dr. Vincent Chevrier

1 Reduce Ore with Carbon
CCUS, carbon looping, biomass, plastics, and beyond

Dr. Halle Cheeseman, Prof. Antoine Allanore

2 Reduce Ore Electrochemically
Ore electrolysis (disproportionation)

Prof. Zak Fang & Dr. Joe King, Dr. Martin Pei

3 Reduce Ore with Hydrogen & Hydrogen Plasma
Non-C renewable reductants, e.g. H_2 and H_2 Plasma

Dr. Peter de Bock, Prof. Chenn Zhou, Prof. Tyamo Okosun

5 Process Intensification
Decarbonized heating, reaction monitoring/modelling, AI/ML

Dr. Joe Marriott, Dr. Jack Lewnard

7 Tracking Impact: CO_2e Emissions and Beyond
LCA, GHG emissions tracking, waste, water, etc.

BOF or EAF → molten steel → casting, rolling, etc. → fabrication →

integrated steelmaking

intensified steelmaking ("direct" to powder or part)

4 Value Chain Innovation: Better & Emerging Products
Powders & NNS, purer Fe, alloys, etc.
Cross-cutting: Dr. Doug Wicks & Dr. Peter de Bock
Cross-cutting: Dr. Vincent Chevrier & Dr. Katie Daehn

Dr. Joe King & Dr. Dave Tew, Dr. Katie Daehn

6 Circular Economy
Demand reduction, improving scrap, systemic material efficiency

8 Tech to Market
Markets, metrics, partnering, investment, deployment, etc.

Patrick Finch, Prof. Mark Johnson, Traci Forrester, Ben Kowing, Pedro Prendes-Arias, Dr. Kevin Zeik, Dr. Dave Miracle

arpa·e
CHANGING WHAT'S POSSIBLE

Anonymous poll time! – Please see link in the Webex chat!

https://arpa-e.energy.gov

christina.chang@hq.doe.gov